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LIFE CYCLE ASSESSMENT OF PHOTOVOLTAICS: PERCEPTIONS, NEEDS, AND CHALLENGES

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ABSTRACT

High impact publications recently depicted PV technologies as having higher external environmental costs than those of nuclear energy and natural-gas-fueled power plants. These assessments are based on old data and unbalanced assumptions, and they illustrate the need for LCA data describing the continuously improving photovoltaic systems and the inclusion of social benefits in this comparison.

1. INTRODUCTION

Life Cycle Assessment (LCA) is a framework for describing the possible lifespan environmental impacts of material/energy inputs and outputs of a product or process. LCA is used in evaluating the environmental impacts of energy technologies, and its results are increasingly used in decisions about R&D funding and energy policies. Publications written to inform energy decision-makers in the European Community [1] and in Australia [2] indicated that photovoltaics have relatively high environmental impacts. These impacts result from the fossil-fuel-based energy currently used in the production of materials for solar cells, modules and systems. One issue with these comparisons is that the photovoltaic systems were assessed based on old data [3]. Another issue is that these comparisons are based entirely on material- and energy-flows; they ignore the external costs related to energy security, fuel depletion, mining, and accidents in fuel transportation. In the ExternE study [1], the health and environmental risks from major nuclear reactor accidents and long-term (4,000 yrs) high-level nuclear waste (HLW) storage were assigned an almost zero probability.

2. CURRENT STATUS OF LCA OF PHOTOVOLTAIC SYSTEMS

Hagedorn [4] a pioneer in the field of LCA extensively analyzed material-and energy-flows in silicon solar-cell production facilities in Germany around 1990, covering prototypes of crystalline-and amorphous-silicon module technologies. Because of its thoroughness and extensive documentation (published only in German,) his work formed the basis for many later studies and, in fact, it was the underlying dataset for the ExternE analysis of PV systems. Later studies partially updated Hagedorn's data on silicon yields and energy consumption [5-9]. Jester and Knapp [10] used actual records of energy use in a production plant to assess energy payback times for monocrystalline silicon- and CIS modules, but their estimates can not be scaled-up. Generic, scalable estimates were included in the Ecoinvent 2000 [10] and ECLIPSE databases [11]. Both are mainly based on current literature sources, but still rely on Hagedorn's data for some material flows. Early LCA of thin-film technologies have been conducted [12,13,14,9], but their estimates are not representative of current and expected future efficiencies. In the following, we identify technical needs in the PV-LCA resources, and outline a plan to satisfy them.

3. TRENDS AND DATA NEEDS

3.1 Emissions in Metals Production

Significant changes have occurred in the emission factors associated with producing the metals used for semiconductors, coatings, and frames in PV modules. Emissions from smelters were greatly reduced over the last ten years as companies strove to improve their environmental records. However, the databases used for Life Cycle Analysis (LCA) models often are outdated. A cursory review of the major LCA databases, EcoInvent (Swiss Centre for Life Cycle Inventory), DEAM (TEAM), and IVAM4 (University of Amsterdam), revealed some emission factors based on old information from 1980, with most sources dating before the mid 1990s. In addition, the "minor" metals (Cd, Se, Te, In, Ga and Ge) that are by-products of base metal smelting (e.g., Cu, Zn, Pb, Al), either are not included or are inadequately described. .

3.2 PV Manufacturing

The data needed for assessing the material- and energy-factors in PV manufacturing are process- specific, changing as the process evolves. For mono- and multi-crystalline Si, many older process data are available, and one might be tempted to use them after updating for wafer thickness and silicon utilization rates. However, the last decade saw changes in many parameters in Si feedstock production, wafer sawing, in-house silicon recycling, and cell processing. Validated data from actual production lines are needed for these and for newer processes (Table 1). For thin-film processes, limited studies on a-Si, CIS and CdTe exist and they need to be updated and augmented (Table 2). Future scenarios must consider better material utilization rates, and thinner layers.

3.3 PV Use

Photovoltaic systems do not emit any pollutants during their operation, but there has been concern about accidental emissions during fires of residential PV systems. Fire-simulating tests for double-glass CdTe modules, showed such emissions to be negligible [15,16]; similar experiments on double-glass CIGS modules are in progress. No data are available for other module types.

3.4 PV End-of-Life (Disposal/Recycling)

There are very few data on potential emissions from end-of-life PV modules. Here, the technical needs depend on assumptions about pathways for disposal and/or recycling. A first LCA study in PV module recycling was conducted for a pilot process for c-Si modules at Deutsche Solar [17]. Other studies were limited to the environmental fate of Cd in CdTe PV modules [15].

4. METHODOLOGICAL ISSUES

4.1 Change-oriented LCA

Technology evolution

How can one reasonably assess a new and emerging technology? Most studies do not consider technological evolution in evaluating different options. For currently commercial photovoltaics technologies, learning curves and a clear understanding of associated constraints allow us to reasonably forecast the near-term future trends. One of the key improvements of PVs in the past few decades has been the increase of cell electric conversion efficiency. Improving the efficiency of PV modules, results not only in direct cost savings but also on proportional external cost reductions (cents/kWh). While PV modules become more efficient, they also use less material as cells become thinner and thinner and frames become obsolete. Such progress can be described by considering a "near-term scenario" or "likely 3- or 5-yr scenario" in addition to the "current scenario" in all assessments of PV technologies. The "likely 3- or 5-year scenario" might include foreseeable reductions of emissions in metal production based on clearly established trends.

Restructure of the Electricity System

Also future scenarios could consider a time-horizon wherein a sizeable contribution of PV and other "clean" technologies is expected in the country's electricity generation mixture. The mixture of technologies used for power generation is likely the greatest factor in environmental externalities. By using cleaner energy in materials' production and in PV manufacturing, the associated emissions would be lower [18]. This is exemplified by a detailed assessment of the environmental externalities in the Greek electricity system, based on the ExternE methodology under different scenarios of renewable energy sources (RES) penetration. Adding RES in the existing system produced small external benefits, but in a restructured system with old and highly polluting lignite units gradually replaced by new cleaner technologies, a 14% increase of the RES contribution resulted to a reduction of external costs by 14 to 17 ¢/kWh in a 10-yr period (2000-2010) [19].

4.2 Comparisons of Energy Technologies

Although the external costs of energy generation are, by definition, those related to environmental and social impacts that are absorbed by society, the major comparisons of energy technologies, discussed in the introduction, are limited to routine environmental impacts. The ExternE assessments estimated the external costs of nuclear energy in central Europe to be 0.1-0.7 euro¢/kWh based only on health and environmental damage functions associated with routine operations in a peaceful and secure world. Accident-related health, safety and ecological risks were excluded or not fully accounted for in the reviewed assessments; these include risks in fuel mining, fuel transportation, and long-term storage of spent nuclear fuel. It is noted that the pioneers on the quantification of environmental externalities, Hohmeyer [20] and Ottinger et al. [21] included social costs for nuclear and fossil which results to external credits of renewables. By just including the external costs related to fuel depletion, environmental damage and subsidies, Hohmeyer[20] assessed that the minimum external costs of nuclear energy in Europe are in the range of 6-42 cents/kWh, versus the 0.1-0.7 cents/kWh estimated from the ExternE studies. In addition, the following are external costs to tax-payers that must be included in such comparisons: Fiscal externalities associated with energy security (e.g., expenses of: physically protecting power plants, supply disruptions, and accident insurance); risks to energy independence and national security (e.g., control of fuel resources, depleting resources); social cost of military conflicts; unsustainability for future generations; and the risk of increased nuclear-weapon proliferation. These vulnerabilities and externalities have been discussed recently [22,23], but they have not yet been expressed in monetary values.

5. RESOURCES AND STRATEGY FOR MEETING CHALLENGES

The LCA community in Europe, the United States, Japan, and Australia includes several researchers of life cycle PV-related issues. Our goal is to link them (e.g., http://www.ecn.nl/zon/products/ehs/index.en.html), joining forces in filling the technical data gaps, producing useful assessments for PV, and in contributing to useful comparisons of PV with other electricity-generating technologies. The following are new and ongoing LCA programs that are part of this effort.

1. The Ecoinvent2000 database updated process and emissions data for silicon purification and for the Czochralski ingot growing, and produced estimates for future PV production technologies.
2. The ECLIPSE project produced new LCI data for emerging energy technologies, including PV. New insights were developed on electronic grade poly-Si production, $SiHCl_3$ production, and internal product recycling.
3. The CRYSTAL CLEAR project is a large 5-yr EU-funded project aimed at improving crystalline silicon PV technology. It has a component on sustainability that will describe input/output of materials/energy and determine possible environmental impacts via Life Cycle

Assessments in x-Si processing steps. Also it aims to improve x-Si module recycling technology

4. The SENSE (Sustainability Evaluation of Solar Energy Systems) project is another large European project that will amass new LCA data for a-Si, CIS, and CdTe. However, it is not known yet to what extent these data will become publicly available.

5. The US Department of Energy's PV Environmental Research Center at Brookhaven (BNL-PV-EHS) is analyzing environmental inventories for the production of metals and semimetals used in photovoltaics.

6. The University of Michigan is conducting a LCA of the new UniSolar's 30MW a-Si facility in Michigan.

7. The BNL-PV-EHS will conduct an LCA of CdTe PV technology, using data from First Solar's manufacturing facility in Ohio.

8. The BNL-PV-EHS and various universities plan to develop tools to quantify the social costs of fossil- and nuclear-technologies associated with risk avoidance and security, which represent external credits to PV.

6. DISCUSSION

The potential environmental impacts of energy technologies are being closely scrutinized as concerns for the environment increase and different technologies compete for the marketplace and for R&D funding. It is widely accepted that the total costs of electricity generation are their direct costs plus the external (societal and environmental) costs during all the stages of the system and the fuel cycles. Publications with high political impact recently presented unbalanced and incomplete comparisons of nuclear energy against photovoltaics. We challenged such comparisons, engaged the concerned parties, and linked resources to correct and complete them. Our efforts aim at a) adequately describing the LCA and external costs of current and near-term future photovoltaics, and b) quantifying and including the external costs of nuclear- and fossil-fuel power generation missing from these comparisons with PV (e.g., security risks and protection costs, nuclear proliferation, risks from accidents or sabotage in fuel mining, transportation and use, potential high-consequence accidents in nuclear power plants, and long-term HLW storage).

Twofold benefits to the PV industry will subsequently accrue: a) optimization of process and materials design and selection for minimum total costs, and, b) better projection of the environmental benefits of photovoltaics.

The PV industry is doing a good job in maintaining safe and environmentally friendly production facilities, but needs to be more proactive in projecting this image. A successful implementation of the strategy we outline requires the industry's cooperation in supplying the technical data needed to complete useful LCAs. Accurate, well-balanced, and transparent assessments can only help the PV industry and society at large.

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Table 1. Data Needs for Life Cycle Analysis of Crystalline Si Photovoltaics

	Silicon yield	air emissions	energy consumption	solid waste	Remarks
Crystalline silicon – **current** prod. technology					
- EG-Si feedstock (Siemens process)	**LD/NU**	**ND**	**LD/NU**	**ND**	energy data are crucial; $SiHCl_3$ recycling data needed
- cryst. (CZ *and* casting)	A	NN	**LD/NU**	**ND**	CZ energy uncertain; effect of internal Si recycling unknown
- wafering (incl. cleaning)	A	**NU** *(NOx?)*	A	A	slurry recycling?
- ribbon techn. (EFG, SR)	**LD**	NN	**ND**	**ND**	
- cell +module prod.	A	**LD**	A	A	Uncertainty, overhead energy use
- system use	NN	NN	NN	NN	
- EOL disposal / module recycling	**LD***	**LD***	A*	A*	lead-free soldering needed; little recycling experience
Crystalline silicon – **new** prod. technology					
- SoG processes	**ND**	**ND**	**LD**	**ND**	
- new ribbon techn. (RGS)	**LD***	NN	**LD***	NN?	
- dry etching processes	NN	**LD**	**ND**	**LD**	emissions/abatement cost FCs
- new contacts	NN	**ND**	**ND**	**ND**	replacement for silver needed
Thin film c-Si					
- substrate material	NN	**ND**	**ND**	**ND**	
- dep. + processing	**LD**	**ND**	**ND**	**ND**	

Table 2. Data Needs for Life Cycle Analysis of Thin-Film Photovoltaics: **Air Emission** Factors

PV Type	Materials	Material Production/Purification	PV Production	PV use (fires)	PV Disposal /Recycling
CIGS	Cu, Mo	**NU/ NA**	A	**NU**	**NA**
	Ga, Se	**NA/ NA**	A	**NU**	**NA**
	Zn, ZnO, Cd	A/ A	A	**NU**	**NA**
CdTe	Cd, Te	A/A	NA (VTD)	A (dbg)	**LD**
a-Si	Mo	**NU/ NA**	A	**NA**	NN
	Ge, GeH_4	**NA**	A	**NA**	NN
	SiH_4, SiF_4	**LD/NU**	A	NN	NN
Encapsulation	EVA	**NA**	NN	A	A
Bus bar	Solder (Pb, Sn, Zn)	**NU**	NN	NA	A
Grid	Silver Plate	**NU**	NN	NA	NA

A -Available
LD - Limited data, * only data for a pilot process
NU –Need to be updated (outdated numbers in databases)
NA – Not Available; ND - No Data
NN –Not needed (not applicable or emissions are neither toxic nor greenhouse-gases)
dbg = double-glass modules VTD –Vapor Transport Deposition